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DEVELOPMENT OF A HIGH FLUX CONDUCTION CALIBRATION APPARATUS

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ABSTRACT

A new conduction calibration apparatus has been designed to deliver heat fluxes up to a maximum of 100 kW/m^2 with an established goal of ± 5 % precision. This system will provide a close to purely diffusive (as opposed to radiative) heat flux boundary condition and, when compared to the gauge's response in the National Institute of Standards and Technology (NIST) radiative calibration facility, act as a check on the sensitivity of a heat flux gauge to the mode of heat transfer. A platinum-plated copper block heated electrically with 2 kW power is designed to produce uniform temperatures up to 750 K across its face. A cold plate will be maintained around 290 K through pool boiling using a liquid refrigerant and a remote condenser. A 1 mm wide helium filled gap between the hot plate and the sensing surface of a cooled heat flux gauge will provide the high conductive fluxes desired (while limiting radiation to a few per cent and avoiding the uncertainties associated with contact resistance). Detailed numerical modeling of the device is being used to identify limitations and evaluate alternatives in the design, and to analyze the level of uncertainty associated with the facility. A description of the apparatus and the results of preliminary modeling are reported.

INTRODUCTION

A common heat flux gauge as represented in Fig. 1 responds to the total flow of energy through a surface layer of finite thickness, whether the energy originates as an electromagnetic wave or molecular motion. The gauge cannot avoid affecting the local heat transfer to a certain degree, so that the accuracy of its response is inextricably linked to the boundary conditions at the time of calibration.

A program to expand the range of boundary conditions for the precise calibration of heat flux transducers was begun at the National Institute of Standards and Technology (NIST) following a workshop in 1995, which was organized to define the industry heat flux measurement needs (Moffat and Danek, 1995). Radiative, convective and conductive modes of heat transfer were all of concern. At that time, standard methods already existed at NIST for calibrating thermal radiation detectors at flux levels up to 10 kW/m^2 using controlled blackbody cavities, and up to 40 kW/m^2 using a monochromatic laser radiation source (Murthy et al., 1997a). The primary need for radiation calibrations was determined to be an increase in flux levels without a sacrifice in precision. To accomplish this, the radiation facilities were modified and better characterized to account for temperature, convection, geometric, and material nonuniformity effects on the calibration of the gauges. Using a variable temperature blackbody with a maximum temperature of 2900 K and a 4 W electrically calibrated radiometer, gauges were successfully calibrated to 100 kW/m^2. To reach 200 kW/m^2, a 20 W electrically calibrated radiometer and a 3200 K blackbody will be developed in cooperation with industrial partners. (The status of this work is reported in another paper in this session by Murthy et al. [1997b])

No national facility existed at all for calibrating heat flux gauges in a purely convective environment. To remedy this, a convective heat transfer wind tunnel was designed to produce a precisely-controlled, shear-flow over an electrically heated plate in which a transducer is flush-mounted. A paper by Holmberg et al. (1997) explains how air at a cooler temperature flows through a 0.3 m by 0.3 m duct and a 30:1 area contraction 2-D nozzle to control the boundary layer profile and minimize turbulence. The gas temperature and velocity are variable, with heat fluxes at the surface between 0.5 kW/m^2 and 5.0 kW/m^2 attainable.

A precise and reliable test method for determining the conductivity of different solid materials is described in ASTM Standard C 177. The original apparatus constructed at the National Bureau of Standards (the precursor of NIST) used a guarded-hot-plate with a distributed area heater, but the most recent NIST version incorporates a line heat source (Tye, 1964). Zarr and Hahn (1995) describe the apparatus and the range of conditions that can currently be accommodated. The operating temperature limits are - 40 °C to 100 °C on the cold side, and a maximum of 150 °C on the hot side. Specimen conductances around 7 W/m^2-K can be measured with a precision of 1 %. The same apparatus can be used to calibrate heat flux transducers by inserting a standard material of

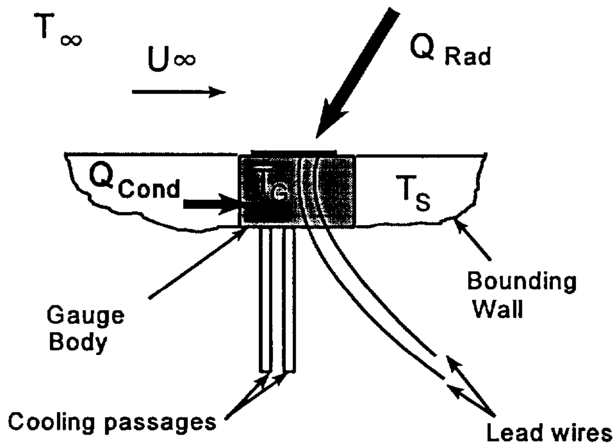

Figure 1. Sketch of heat flux gauge at boundary, showing multiple temperatures and modes of heat transfer.

known thermal conductivity and thickness. Heat fluxes in the range of 0.1 kW/m^2 are typical. A new high temperature apparatus being installed in the laboratory will increase the maximum temperature to 750 K with heat fluxes estimated up to 0.5 kW/m^2.

Neither the guarded-hot-plate nor the convection facility produce the high heat fluxes experienced by transducers in many industrial and research applications. While heat fluxes in excess of 100 kW/m^2 are provided in the NIST radiation facility, large errors can be encountered when exposing a radiation-calibrated transducer to a purely convective or mixed heat transfer environment (Brookley and Liller, 1994). A new calibration fixture based on pure conduction has been developed to overcome this deficiency. The heat transfer in the new high flux conduction apparatus has been simulated numerically as an integral part of the design process. The rationale, goals, and design details of the new fixture are presented in this article.

RATIONALE AND OBJECTIVES

Heat fluxes in excess of 100 kW/m^2 are common in fires, furnaces, combustion engines, supersonic wind tunnels, and materials processing. These high fluxes are generated by a combination of high temperatures, radiation, and large fluid velocities. The control of any of these processes for a period long enough to perform a calibration at a precision of ± 5 % is most unlikely, and because the processes involve turbulent flow and radiation, the heat flux at the boundaries can not be numerically modeled with the degree of confidence required for a calibration facility.

The flux levels of the standard guarded-hot-plate is over two orders-of-magnitude below the goal for the new facility. While new designs which incorporate higher power heaters and higher temperature materials are conceivable, the issue of contact with the heat flux gauge must be addressed. Contact resistance is highly uncertain, and produces an environment totally different from the convective boundary condition to which the transducer may be subjected in application.

To circumvent the problems associated with a direct contact guarded-hot-plate, the new calibration fixture is based upon conduction through a gas layer. Even in high velocity flows, the heat transfer through the sublayer at the wall is controlled by conduction, which permits the gas-conduction-calibrated gauge to be applied to a convective environment with greater confidence.

The energy transfer in the conduction apparatus can be idealized as flowing between two infinite parallel plates at hot and cold temperatures, T_h and T_c, separated by a gap of dimension δ. The total heat flow, Q_{tot}, per unit area, A, is the sum of the convective and radiative flows (Q_{conv} and Q_{rad}) per unit area. The convective heat flux, Q_{conv}/A, can be represented as

$$\frac{Q_{conv}}{A} = Nu_\delta k \frac{(T_h - T_c)}{\delta} \tag{1}$$

where Nu_δ is the Nusselt number based upon the plate spacing and k is the thermal conductivity at the average temperature of the gas. Nu_δ approaches unity when the value of the Grashof number, Gr_δ, is less than 1700 (Holman, 1990), where

$$Gr_\delta \equiv 2\frac{(T_h - T_c)}{(T_h + T_c)}\frac{g\delta^3}{\nu^2} \tag{2}$$

Assuming a kinematic viscosity of 5x10^{-5} m^2/s and hot and cold temperatures of 750 K and 300 K, the limiting condition of unity Nusselt number occurs for plate spacings less than about 3 mm.

The radiation transfer between the plates is given by

$$\frac{Q_{rad}}{A} = \frac{\sigma(T_h^4 - T_c^4)}{(1-\epsilon_h)/\epsilon_h + 1 + (1-\epsilon_c)/\epsilon_c} \tag{3}$$

with ϵ_h and ϵ_c the emissivities of the hot and cold plates, respectively, and σ the Stefan-Boltzmann constant. If one defines the non-dimensional temperature, Θ, total heat flux, Ψ, and the radiation/conduction parameter (with $\epsilon_h = \epsilon_c = \epsilon$), β, as

$$\Theta \equiv (T_h/T_c), \quad \Psi \equiv \frac{Q_{tot}/A}{kT_c/\delta}, \quad \beta \equiv \frac{\epsilon\sigma T_c^4}{(2-\epsilon)}\left(\frac{\delta}{T_c k}\right) \tag{4}$$

then the total heat flux can be expressed by the following equation:

$$\Psi = (\Theta - 1)\left(1 + \beta\frac{\Theta^4 - 1}{\Theta - 1}\right) \tag{5}$$

Figure 2 is a plot of Eq. (5) showing the impact of the temperature ratio on Ψ for various values of the radiation/conduction parameter. A value of β equal to zero implies pure conduction, with the result that the heat flux is linearly proportional to the temperature ratio. Increasing values for β cause the straight line to bend upward, especially for large values of Θ. When the gas chosen is helium, and the plates are assumed to

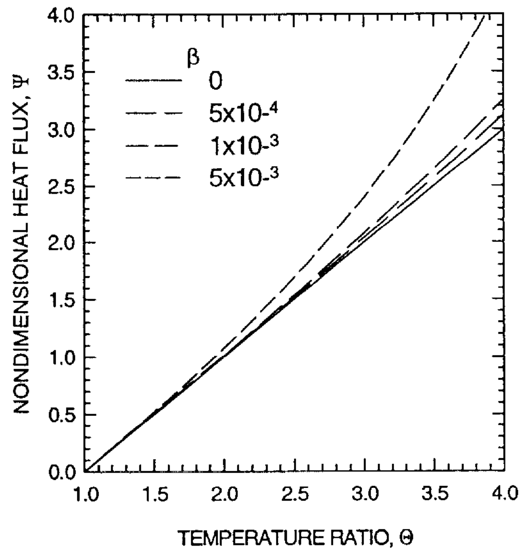

Figure 2. Impact of temperature ratio and radiation/ conduction parameter on non-dimensional heat flux beween infinite parallel plates.

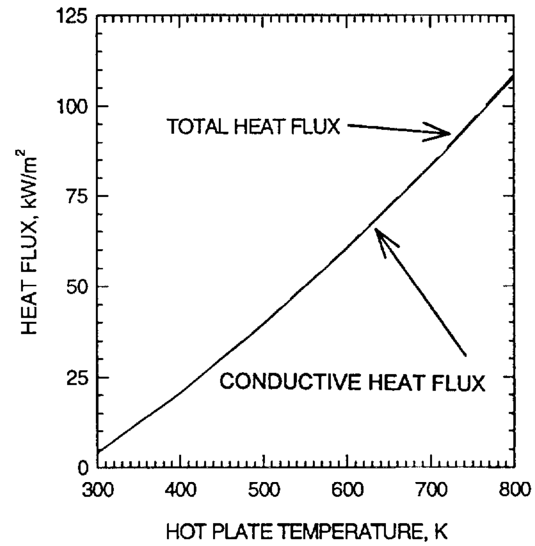

Figure 3. Heat flux between infinite parallel plates spaced 1 mm apart, with helium gas in between. Cold plate temperature is 273 K, ϵ=0.07.

have an emissivity of 0.07, then β takes on a value of 2.87×10^{-4} at 273 K. The dimensional heat flux is plotted in Fig. 3 for this case with a plate spacing of 1 mm. The solid line is conduction alone. The slight curvature is due to the temperature dependence of the thermal conductivity of helium with temperature. The dashed line in Fig. 3, almost coincident with the pure conduction line, is the total heat flux. The figure clearly shows that the design goal of 100 kW/m^2 is attainable for a hot plate temperature of about 760 K with a negligible contribution due to radiation.

FACILITY DESCRIPTION

The conduction calibration apparatus consists of the hot plate, the cold plate, a helium chamber, a power supply, a boiler/condenser housing, and a chiller. (See Figs. 4 and 5.) The hot plate is constructed of a 100 mm diameter by 38 mm thick disk of pure copper, with seven 300 W rod-type heaters inserted from the back, and the front side polished and plated with platinum. The cold plate is made of pure copper of similar dimensions, with the side facing the hot plate also platinum coated. Cooling fins are machined into the back side to provide an extended surface area for enhancing the heat transfer. A 1 mm gap is maintained between the hot and cold surfaces using three specially machined stainless steel pins, 13 mm long, and spaced every 120 ° on the circumference. The heat flux gauge to be calibrated is located on the axis of the cold plate held firmly within a brass collar with a 12 mm outside diameter and an inside diameter machined to accommodate the gauge.

A stainless steel chamber, 170 mm in diameter and 140 mm high, encloses the copper plates, with the cold plate forming the top. A sectional view of the assembled chamber is shown in Fig. 4. Having the cold plate on top permits a liquid pool to be in direct contact with the back of the plate, improving the efficiency by which heat can be removed. Instabilities in the intervening gas are not generated by the hot plate below because the Grashof number is less than 10. Pyrex glass windows on the side of the housing permit an edge-on view of the gap and the heat flux gauge surface. The chamber is first evacuated and then helium is added to about atmospheric pressure through 6 mm stainless steel tubes. The electrical power leads for the rod heaters and thermocouples are brought out through the bottom of the hot plate.

Three precision DC power supplies are used to control the temperature of the hot plate. The six outer heaters are connected alternatively in parallel to two individually controlled 7 A, 150 V power supplies. Fine control of the temperature at the center of the hot plate, directly opposite from the heat flux gauge, is maintained with a single heater connected to a 2.5 A, 100 V power supply. The temperature is measured 12.7 mm from the axis and 1.5 mm beneath the surface using a 1.6 mm diameter, sheathed, chromel-alumel thermocouple.

At the highest design fluxes, the heat transfer coefficient necessary to cool the upper plate can be obtained only through a change of phase. Trichlorofluoromethane (R-11) absorbs 180 kJ/kg when it boils at atmospheric pressure (24 °C). Peak heat fluxes well above the 100 kW/m^2 transferred across the helium gap should be dissipated easily from the copper block by a boiling pool of R-11. The R-11 will be condensed on the outer surface of about a 60 m length of 6 mm diameter copper tubing through which a water/ethylene glycol solution maintained at 15 °C will flow. A chiller with about 5 kW cooling capacity at 15 °C will be used to keep the liquid solution at a constant temperature.

A block diagram of the major components of the high flux conduction calibration facility is shown in Fig. 5.

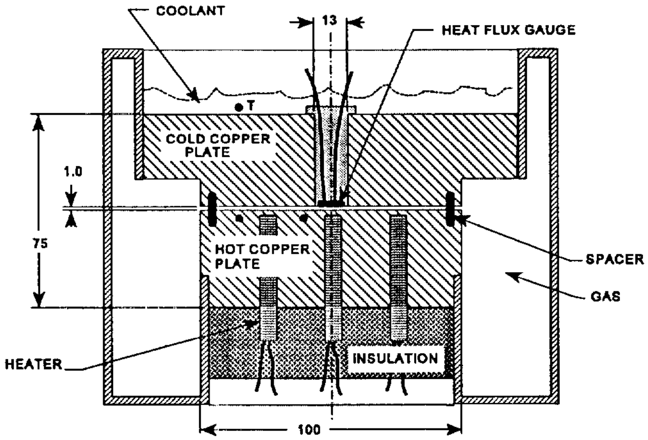

Figure 4. Cross-sectional view of high flux conduction apparatus showing hot and cold copper plates, 1 mm gap and location of heat flux gauge.

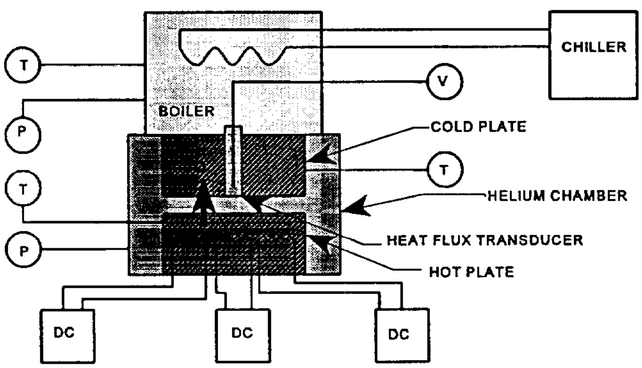

Figure 5. Block diagram of high heat flux conduction calibration facility. T= temperature, P= pressure, and V= output voltage measurement; DC= power supply.

THREE-DIMENSIONAL HEAT TRANSFER MODEL

Commercial, finite-difference thermal modeling software, PC3D,[1] was used for this study, though any similar software designed for heat conduction modeling should be satisfactory. A solution was achieved when the heat balance (the difference between the total applied power minus the power flowing out of the model at its boundaries) was less than 1% of the total applied power and there was no model node that had

Table 1. Thermal conductivity of materials used in modeling of fixture

Material	Thermal Conductivity (W/m-K)
Copper (main fixture)	400
Helium (gas section)	0.2
Stainless Steel (spacers, shell)	14
Insulation	0.1
Brass (gauge)	110

a temperature change greater than 0.001 °C between successive iterations.

Because of the symmetry of the fixture, only a one-sixth section of the total volume needed to be modeled. Schematics of the model geometry viewed from the top and from a side of the model section are shown in Fig. 6. The number of elements used in the model was 23 in the radial, 8 in the azimuthal, and 35 in the vertical directions for a total of 6440 volumes in the one-sixth section. Only conduction within the fixture is assumed. The analysis already discussed shows that the heat transfer by radiation across the gas section will be less than a few percent of that conducted across that section. Convection from the outside surfaces is accounted for by using a constant heat transfer coefficient of 10 $W/m^2/K$, but it was found that the computed temperatures and heat fluxes near to the gauge were not sensitive to convection from the outside surfaces. Table 1 lists the thermal conductivities of the materials used in the fixture. Temperature dependency of these properties has not been considered.

NUMERICAL RESULTS

The simulations have been designed to provide answers to several questions and to provide guidance in the operation of the fixture. The simulations have shown that the design temperatures and heat flux magnitudes can be achieved at the gauge position with the heater elements and fixture as designed. They have also shown that while the outside surfaces may have to be insulated for safety reasons, convection from these surfaces should not be significant.

It is desired to have the temperatures as uniform as possible on the faces of the gas section so that the heat flux across the section at the gauge location can be accurately estimated from the temperature measurements made near by. Computation of the heat flux magnitude at the flux gauge surface depends upon being able to relate the temperatures at both faces of the gas section at the gauge location to the temperature measured some distance away and near to the surface. An example of the uniformity that can be achieved is shown in Fig. 7. Shown are the simulated temperature profiles for non-uniform power levels in the heaters (the center heater is dissipating only 10% of the power of the other heaters). Figure 7a shows a cross section of the fixture in the vicinity of the gauge for approximately 164 W applied to each of the radial heaters and 16 W to the central heater (1 kW overall). Figures 7b and c show the temperature profiles along the faces of the cold and hot sides of the gas section respectively. The uniformity of the temperature

[1] Certain trade names and company products are mentioned in the text or identified in an illustration in order to specify adequately the experimental procedure and equipment used. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose.

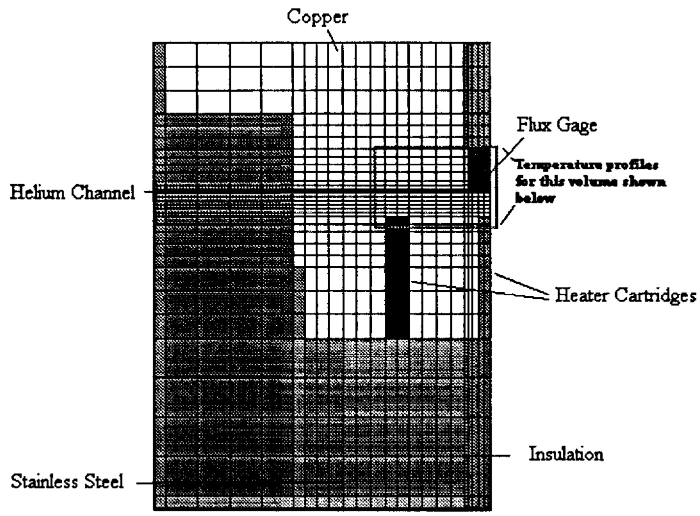

Figure 6a. Modeling geometry side view.

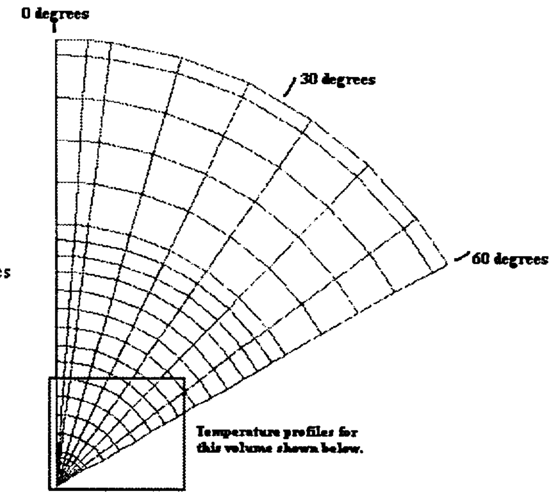

Figure 6b. Modeling geometry top view.

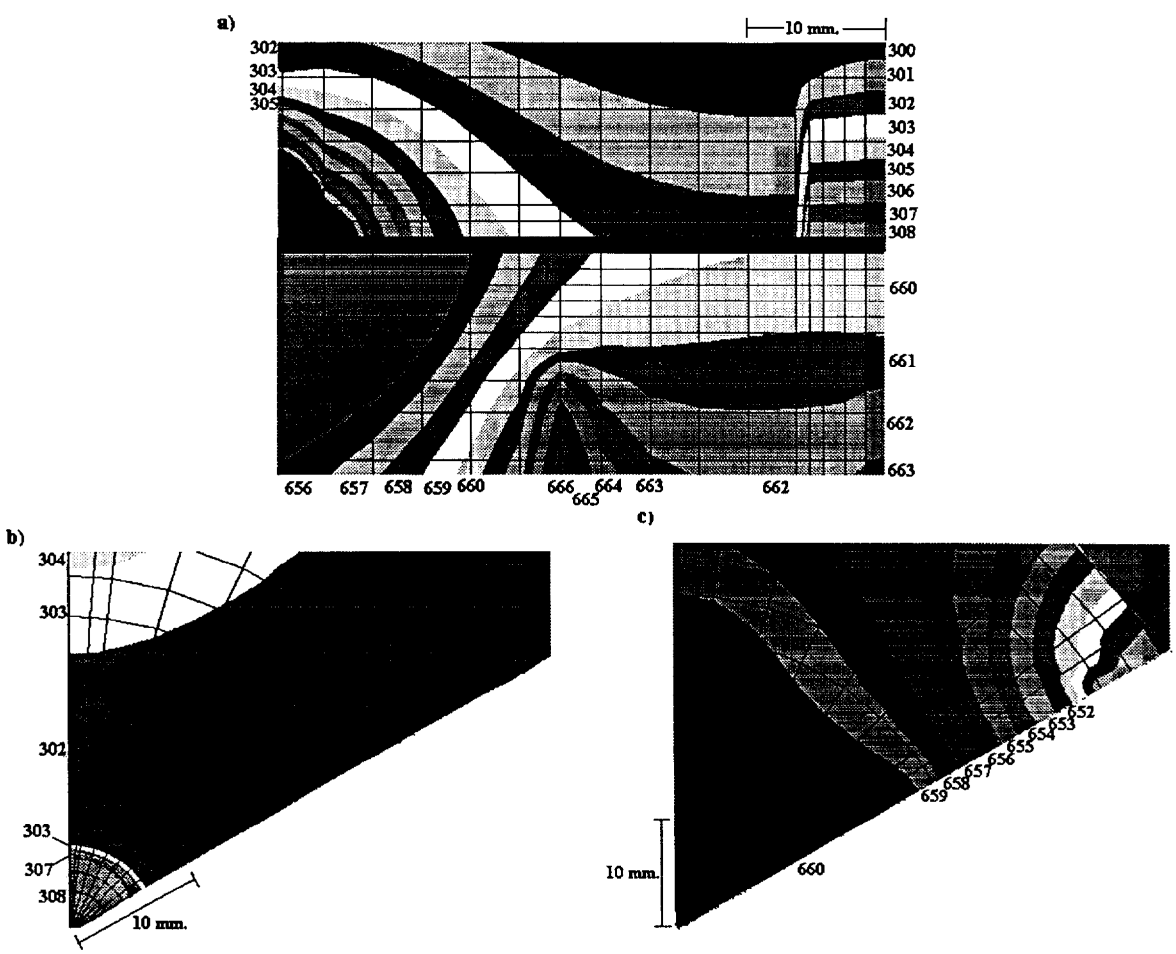

Figure 7. Computed temperatures in Kelvin for nominal 1 kW power dissipation and the cold plate top at 293 K. Center heater is reduced to 10% of average heater power: a) cross section (see box in 6a. above), b) face of cold side, and c) face of hot side of gas section (see box in 6b. above).

is achieved by reducing the power to the center heater significantly below that of the radial heaters. This uniformity of temperature on the hot side is probably sufficient to achieve the desired accuracy of the fixture.

There are more significant temperature variations on the cold side of the gas section where the gauge is located. The gauges to be calibrated will be constructed of various materials and will be housed in packages of different materials with thermal conductivities likely to be different from that of the copper fixture. Also, there will be some interfacial contact resistance between the gauge housing and the fixture. The difference in the thermal properties between the gauge and housing and the fixture can lead to significant non-uniformities in the temperature in the vicinity of the gauge on the cold side of the gas section. This is seen in the temperature profiles in Fig. 7 where the gauge is constructed of brass. No thermal contact resistance is assumed between the gauge and the fixture. As can be seen, the temperatures on the face of the gauge and in the fixture nearby differ by 6 K. Considering that the temperature on the cold side must be measured somewhere outside the gauge, this could present a serious problem. It should be noted that including a contact resistance makes the temperature across the gauge more uniform. This is because the contact resistance tends to thermally isolate the sides of the gauge from the fixture and reduces the quantity of heat that can flow radially out of the gauge into the fixture.

The simulated heat flux at the gauge surface and beyond as a function of radial position and angle is shown in Figure 8. This shows how the presence of the gauge alters the heat flux. The angles designated span the one-sixth section that was modeled. Assuming that the flux can be accurately measured outside but near to the gauge, less than a 2% error would occur between that measurement and the actual heat flux at the gauge location for the brass gauge simulated here. The magnitude of this error would depend upon the difference in effective conductivity of the gauge compared to that of the copper fixture.

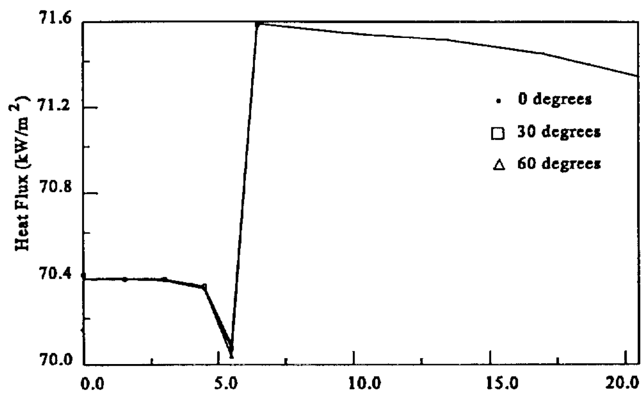

Figure 8. Heat flux versus distance from center for the same conditions as in Figure 7. The azimuthal positions are shown in Figure 6b.

SUMMARY AND CONCLUSIONS

The design and modeling of a high temperature (> 750 K), high heat flux (>100 kW/m^2) conduction calibration fixture has been described. The design eliminates the thermal contact resistance as a source of error by employing a gas conduction section at the face of the gauge being calibrated. Operation in the regime where the Nusselt number approaches unity eliminates convection as a problem and analysis shows that radiation across the gas section accounts for at most a few percent of the heat transfer.

Modeling results show that a suitable uniformity of temperature can be achieved on the heated side of the gas section. Due to unavoidable material differences between the fixture and the gauge being calibrated, though, the temperature on the cooled side and the heat flux across the gas section may be non-uniform in the area of the gauge. The simulations show that for a brass gauge in the copper fixture with a helium gas section, there could be less than a 2 % difference between the measured flux in the area of the gauge and the actual flux through the gauge.

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